Effect of Sand on the Vacuum Consolidation of Dredged Slurry

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Abstract

Vacuum preloading is often used to improve the geotechnical properties of dredged slurry. Although the performance of this method has improved with rapidly developing technology, soil columns usually formed on the drainage boundary induce the decrease of permeability around the boundary, thereby limiting the further development of this method. To address this issue, this paper proposes a method for pretreating the slurry combined with sand prior to vacuum consolidation. This method partially replaces the fine particles with sand to reduce the formation of soil columns. Two groups of vacuum preloading tests were performed to investigate the effect of sand content and sand grain size on the vacuum consolidation of dredged slurry. The test results revealed that for a given sand grain size, increasing the sand content of the sand-slurry mixture increased the pore water drainage and accelerated the dissipation of pore water pressure, thereby increasing the vane shear strength. In contrast, for a constant sand content, the samples containing coarse sand exhibited increased pore water drainage and accelerated dissipation of pore water pressure, thereby increasing the vane shear strength of the soil.

Keywords: dredged slurry, sand, shear strength, vacuum preloading

1. INTRODUCTION

With the developing market economy in China, the demand for land resources is gradually increasing, and many land reclamation projects are developing rapidly. Clay slurry dredged from seabeds has been widely used as the fill material in land reclamation projects for the past few decades. However, the clay slurry possesses a high water content, high compressibility, and low bearing capacity (Chu, Yan, and Yang 2000; Indraratna, Geng, and Rujikiatkamjorn 2010). It is imperative to improve the geotechnical performance of the clay slurry using different engineering methods before conducting any construction on these surfaces.

Vacuum preloading is the most commonly used ground improvement method for increasing the load-bearing capacity of dredged slurry. Since the concept for this method was proposed by Kjellman (1952), the effectiveness and convenience of it have been demonstrated in numerous projects (Tang and Shang 2000; Chai 2005; Yan and Chu 2005; Indraratna et al. 2010). In recent years, with the emergence of new materials and technology, this method has been well developed. Prefabricated vertical drains (PVDs) are usually utilized in this method to distribute the vacuum pressure and discharge the pore water (Chu, Yan, and Indraranata 2008). Caps and tubes can be connected directly with PVDs to reduce the vacuum pressure loss at the sand cushion and to ensure vacuum be transferred into the deep layers (Chai, Miura, and Bergado 2008). Specially designed vacuum pumps can achieve a vacuum pressure below the membrane surface of 80 kPa or even reached 90 kPa in practice for soft clay (Qian et al. 1992). Although the technique of vacuum preloading is well developed, soil columns usually formed on the drainage boundary induce the decrease of permeability around the boundary. This permeability may control the average permeability (Bo, Choa, and Wong 2002) and water drainage, thereby limiting the efficiency of this method. In addition, long lead times, high costs and limited improvement of the treated soil still exist during vacuum preloading projects.

Considering that the technique of vacuum preloading has become mature and that further improvements are limited, some studies have focused on pretreating the dredged soil before applying vacuum preloading. Wu, Broms, and Choa (1992) used fly ash to stabilize soft clay prior to consolidation with vacuum preloading. Furthermore, a chemical stabilization method with vacuum preloading was developed that was shown to be effective for increasing the strength of very soft reclaimed foundations (Wu, Xu, and Zhu 2013). Lin et al. (2014) employed $FeCl_3$ as a chemical conditioner to pretreat sewage sludge and to ensure the effectiveness of vacuum preloading. The optimal percentage of $FeCl_3$ was obtained through testing. Wang et al. (2017) utilized hydrated lime to optimize the properties of dredged slurry, thereby improving the efficiency of vacuum consolidation. In these methods, admixtures are employed in the pretreatment to modify the engineering properties of the soil, leading to a chemical or physical change in the soil. These soil changes may be useful in either accelerating vacuum preloading or improving the efficiency of vacuum preloading.

However, pretreating soil with chemical admixtures is an extra expense that may not be economical. In addition, the chemical agent may impact the environment. Therefore, this study proposes a method of sand modification combined with vacuum preloading. This method is achieved by artificially mixing the dredged slurry with a certain proportion of sand to optimize the geotechnical properties and then consolidating the mixture under vacuum preloading. In this method, sand is added as a fraction of fill material to reduce the use of dredged slurry and to make this approach environmentally friendly.

In this study, a series of model tests were conducted to investigate the effect of sand on the vacuum consolidation of dredged soil. Sand proportion and grain size are the two main factors that were researched in these tests. The vacuum pressure, pore water pressure and discharged water volume were monitored during vacuum preloading. In addition, the water content and vane shear strength after vacuum consolidation were measured to evaluate the effect of sand on vacuum preloading.

2. MATERIALS USED IN THE EXPERIMENTS

2.1 Dredged Slurry

The dredged slurry for the tests was taken from the Oufei project, which is located in Wenzhou, China. The geotechnical index properties were determined according to standard laboratory tests. The slurry consisted primarily of fine clay particles without sand, and its water content was approximately 110%. The liquid limit (W_L) and the plastic limit (P_L) were approximately 81 and 42, respectively. The specific gravity of the soil was determined to be 2.61.

2.2 Sand

The sand used to blend with the dredged soil was a type of quartz sand. This sand was a kind of industry product and divided into different classifications using the unit of Tyler mesh. In this way, each mesh number represent a range of grain size and more than 93% sand has a uniform grain size for each mesh number. So for a mesh number, the sand can be hardly divided to provide a grain size distribution curve. And the grain size occupied the greatest percentage, instead of grain size range, was generally utilized to represent a mesh number. In this study, four different classifications are selected and the equivalent size corresponding to mesh number are listed in **Table 1**. It can be seen from the table that the greater mesh number is, the smaller equivalent size it represent.

3. EXPERIMENTAL PROCEDURE

3.1 Sample Preparation

Because the sand content and sand grain size are the two main factors that affect the properties of a mixture of sand and slurry, the samples were divided into two groups.

In the first group, different ratios of sand to soil (dry weight basis) were designed in five cases: 0%, 5%, 10%, 15%, and 20%. This ratio is generally called the sand proportion or sand content (ω_s) and can be obtained using the following relationship:

$$\omega_s = \frac{m_s}{m_s + m_c} \qquad (1)$$

where m_s, and m_c are the dry masses of the sand and clay, respectively.

In this way, the sand content of the mixtures increases from 0 to 20% at 5% increments in each sample. This group was designed to investigate the effect of the sand proportion on vacuum consolidation. Moreover, this group used a uniform sand grain size (60 mesh) to enable comparison.

The other test group was designed to investigate the influence of the sand grain size on vacuum consolidation. Varying grain sizes of sand (10, 60, 100, 150 mesh) were utilized in this group and a pure slurry sample was also included. Furthermore, a sand content of 15% was controlled in all mixed samples to ensure that their consolidation behaviors (eg. discharged water volume or dissipation of pore water pressure) was sufficiently different from that of pure slurry sample.

The sand-soil mixture was prepared on a dry mass basis, and a predetermined amount of seawater was added to keep the final water content of the mixtures uniform. The dredged soil was first poured into eight separate buckets (40 cm in height and 30 cm in diameter) according to the designed mass. Then, according to varying sand content and grain size, the corresponding mass of sand was thoroughly mixed with the soil in each model bucket. Finally, seawater was added and mixed thoroughly to ensure a uniform final water content of each sample. In each sample, a mass of 31 kg and a water content of 140% was maintained after preparation in the buckets.

3.2 Vacuum Consolidation Tests

The vacuum system and instruments was connected according to the following procedure: First, needles connected to the vacuum pipes were inserted through the filter jacket of the PVDs at specific locations, and the tips of the needles were positioned in the space between the filter jacket and the core of the PVDs. Then, a vacuum gauge was connected at the end of the vacuum pipe to measure the vacuum pressure. In this way, vacuum pressure within the soil or PVDs can be measured conveniently and exactly. Second, PVDs with cap were slowly inserted into the sample to the required depth and location, when the other side of the cap had been connected to an air-water separation flask through a vacuum pipe. This air-water separation flask was utilized to collect the discharged water and measure its weight combined with an electronic scale. The other side of the flask was connected to a vacuum pump through the vacuum pipe. To measure the pore water pressure within the soil, a pore water pressure transducer was lied at the bottom of the model bucket. Finally, one layer of geotextile and two layers of membranes were placed on the surface of the sample in sequence to protect the membrane and to seal the sample from the atmosphere, respectively. The final schematic diagram of the vacuum consolidation apparatus and other details about the test apparatus are shown in **Figure 1**.

After the vacuum pump starts, vacuum preloading is applied on the sample, and consolidation begins. During vacuum consolidation, a vacuum pressure of approximately 90 kPa was maintained below the membrane, and the discharged water was collected in the air-water separation flask.

4. RESULTS AND DISCUSSION

4.1 Pore Water Pressure

The pore water pressure was monitored during vacuum consolidation. The variations in the pore water pressure with time for both groups are plotted in **Figures 2** and **3**.

The pore water pressure responses of samples with different sand contents of 0, 5, 10, 15, 20% under the vacuum preloading are shown in **Figure 2**. Overall the five curves show similar characteristics. Each curves can be divided into three segments with time. In the first segment, the curves reflect a slow decrease in pore water pressure with time. In the second segment, the pore water pressure reduces rapidly. This phenomenon is mainly due to the delayed dissipation of pore water pressure, which has been introduced by Imai and Tang (1992) and Mesri and Choi (1985) with interconnected consolidation tests. They pointed that the dissipation of the pore water pressure started at the drainage boundary and proceeded to areas farther away from the boundary. In this case, the drainage boundary is around the PVDs. Therefore, for the areas near the pore pressure transducer, the dissipation of pore water pressure shows a little reduction in the early stage of consolidation and then has a rapid decrease with the proceeding of water drainage. However, the starting time of the second segment varies for soils containing different sand content. This is because the average permeability was changed after blending with the sand, which was observed from the **Table 2**. **Table 2** shows the coefficient of permeability for each samples after the consolidation. It can be clearly seen from the table that the soil permeability increases with the increasing sand content. Therefore, dissipation of pore water pressure started earlier since the average soil permeability was improved.

In the third segment, the dissipation of pore water pressure reached a steady state and the curves of it converge into one. In this stage, the most consolidation has been completed and the rest of pore water can be hardly discharged, so only very little reduction in pore water pressure occurred. In addition, due to the improved soil permeability, the final pore water pressure reduction increases with increasing sand content and the greatest dissipation of the pore water pressure occurs in the sample containing 20% sand with value of –84.5 kPa.

Figure 3 plots the dissipation of pore water pressure over time in samples with varying sand grain size. The curves of pore water pressure shows the same segments as the foregoing discussion. In addition, because the 15% sand content is controlled in samples containing sand, the curves of these samples exhibit distinct differences in the pore water pressure reduction compared to that of the pure slurry sample. However, among the samples containing varying grain size of sand, only small differences were observed. In particular, the slurry containing sand of 10 mesh exhibits an advantage in dissipating pore water pressure, as it achieved the greatest pore water pressure reduction. These behaviors are caused by changed permeability, which is shown as **Table 2**. **Table 2** indicates that for a given sand content, the coefficient of permeability increases with increasing sand particles size. With the addition of coarser sand, the soil permeability was improved, resulting in a greater reduction in pore water pressure. However, the increase of pore pressure reduction made by sand grain size was small as observed from the **Figure 3**, while the dissipation curves shown in **Figure 2** is clearly influenced by sand content. It can be concluded that the main factor that influence the dissipation of pore water pressure was the sand content compared with sand grain size.

4.2 Discharged Water Volume

To monitor the variation of the discharged water volume with time, the discharged water was collected by the air-water separation flask. In this case, the discharged employed g as the unit, since the water volume was measured by an electronic scale. Measurements for two groups are present and discussed as below.

The variation of discharged volume with elapsed time for samples of the different sand contents are shown in **Figure 4**. The figure showed that the magnitude of discharged water increased linearly after applying the vacuum preloading. However, the rate of the drainage was not a constant, it would gradually slow down with time. This is due to the migration of fine particles towards the PVDs with the water drained from the soil. As the fines migrated towards the vertical drains, a filter soil column was formed around the PVDs, which result in the rearrangement of soil grain, leading to a decrease in permeability (Bo, Choa, and Wong 2002). It is possible that the rate of drainage were mainly controlled by the soil permeability around the PVDs.

It can be also seen that as the sand content increases from 0 to 20%, the final discharged water volume exhibits a corresponding increase. In particular, compared to pure clay soil with a final discharged water volume of 12,639 g, the sample containing 20% sand possesses 13,499 g of discharged water volume. It implied that increasing the sand proportion can strongly improve the discharge capacity of the soil during vacuum preloading. And the measured coefficient of permeability of each sample after vacuum consolidation (shown as **Table 2**) also proved the enhanced drainage capacity. As shown in **Table 2**, the coefficient of permeability (k) increases linearly with increasing sand content, implying that the sample containing higher sand content has better drainage capacity.

Figure 5 depicts the variation of discharged water volume over time with changes in sand grain size. In this case, as all of the samples have 15% sand, their discharged water volumes show clear improvement relative to pure clay soil. However, among the samples containing varying sand grain sizes, particularly the 60, 100 and 150 mesh sands, the grain size has little influence on the discharged water volume. What's more, the 10 mesh grain size exhibits a clear increase in final discharged water volume that is approximately the same as that of the 20% sand sample in group one. These behaviors arise primarily from the varying coefficient of permeability caused by adding sand. **Table 2** establishes that the sample with 10 mesh sand clearly improves the coefficient of permeability (k), whereas the samples blended with the other three sand grain sizes have a similar coefficient of permeability. The enhanced coefficient of permeability facilitates water flow in the soil, thereby improving the drainage capacity.

Thus, increasing sand content can effectively increase water discharge from the soil. It is also speculated that coarse-grain sand leads to higher water discharge during vacuum consolidation.

4.3 Water Content

After vacuum consolidation, the water content of each sample at different depths was measured, and the results are plotted in **Figures 6** and **7**.

The relationship between the water content and the percentage of sand is shown in **Figure 6**. The curve exhibits a substantial decrease in water content with increasing percentage of sand. This behavior shows an opposite rule of that shown in **Figure 6**. In this case, because the total water volume is constant (34 kg slurry with 140% water content), the water content of the soil decreases through water drainage. A higher final water content implies that less water was discharged; thus, the remaining water shows a decreasing trend as the sand proportion increases. It can also be concluded that increasing the sand proportion of the soil can sharply reduce the final water content of the soil after vacuum consolidation.

Figure 7 shows the water content curves for the samples with varying sand grain sizes. Clearly, the sample containing the 10 mesh sand has the lowest water content, which is almost equivalent with the value of the 20% 60 mesh sand in **Figure 6**. And the water content values for all the samples containing sand are lower than that of pure clay soil, the differences in the water content among the samples containing sand of 60, 100, and 150 mesh are not obvious. It is speculated that in a certain proportion of sand, coarse-grain sand can reduce the final water content after vacuum consolidation; however, grain sizes smaller than 60 mesh have little influence on the final water content.

4.4 Vane Shear Strength

The vane shear strength was tested after vacuum consolidation, and the relationships among the vane shear strength, the grain size of sand and the sand proportion are plotted in **Figures 8** and **9**.

Figure 8 depicts the relationship between the vane shear strength and the sand content. This figure shows that the vane shear strength gradually increases as the sand content increases from 0 to 20%, reaching a peak value of 29 kPa for 20% sand at a depth of 5 cm. This behavior may be due to sand replacing clay particles, thus increasing the sand content and forming a skeleton with a higher shear strength (Kim, Kim, and Zhuang 2016). In this case, the shear strength of the mixed soil is controlled primarily by the soil structure but is also affected by floating sand (Vallejo and Mawby 2000; Polito and Martin Ii 2001; Yamamuro and Covert 2001; Bahadori, Ghalandarzadeh, and Towhata 2008). Consequently, this result indicates that the shear strength is significantly influenced by the sand content and that higher sand proportions obtain higher strength soil when the sand content is less than 20%.

Figure 9 presents the relationship between the vane shear strength and the sand grain size. In this case, because the sand proportion is fixed at 15%, the difference between the sand-clay mixture and the pure clay soil is clear. The soil containing the 10 mesh sand exhibits the maximum vane shear strength, and this strength decreases with more finer sand. Thus, coarse-grain sand may more effectively improve the vane shear strength. However, it is notable that the vane shear strength at a depth of 5 cm is lower than that in the deep layer for the 10 mesh sand, whereas the opposite trend is shown in the other samples. This inversion may result from a higher density of large grain particles. As the density of these particles is greater than that of the clay slurry, this sand gradually sinks under the action of gravity, leading to aggregate higher concentration of large particles in the deep soil layer. This concentration may be useful for forming a strong link structure that possesses high resistance and improves the shear strength.

5. CONCLUSION

This study investigated the behavior of soil containing different proportions of sand and varying grain sizes of sand under vacuum consolidation. The vacuum pressure, pore water pressure and discharged water volume were monitored during vacuum consolidation. The water content and the vane shear strength of the samples were measured after vacuum consolidation. The following conclusions can be drawn from the test results:

1. For a given sand grain size, the dissipation of pore water pressure, discharged water volume, water content, and vane shear strength are dependent on the sand content: the greater the sand content, the greater the pore water pressure, discharged water volume, vane shear strength, and lower the water content.
2. The permeability changes after adding the sand into the slurry, which may be the main reason for the different behaviors of vacuum consolidation.
3. It is suggested that for a given sand grain size, soil with a high sand content is easier to consolidate when the sand content ranges from 0 to 20%.

4. In general, sand grain size has a little influence on the vacuum consolidation except the 10 mesh sand. And for a certain sand content, adding coarser sand into the slurry may facilitate the vacuum consolidation with water drainage when the sand grain size ranges from 0 to 2 mm.
5. Compared with the influence of sand grain size, sand content may have a stronger effect on the vacuum consolidation.

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Table 1. Particle size conversion table

Mesh	10	60	100	150
mm	2.000	0.250	0.149	0.106

Table 2. Coefficients of permeability for each sample

Sand (Group 1)	Coefficient of permeability k (cm/s)	Sand (Group 2)	Coefficient of permeability k (cm/s)
0% (0)	8.738×10^{-8}	0 (0%)	8.738×10^{-8}
5% (60)	1.185×10^{-7}	150 (15%)	7.331×10^{-7}
10% (60)	4.273×10^{-7}	100 (15%)	6.392×10^{-7}
15% (60)	8.387×10^{-7}	60 (15%)	8.387×10^{-7}
20% (60)	2.111×10^{-6}	10 (15%)	1.387×10^{-6}

Figure 1. Schematic diagram of the vacuum consolidation apparatus.

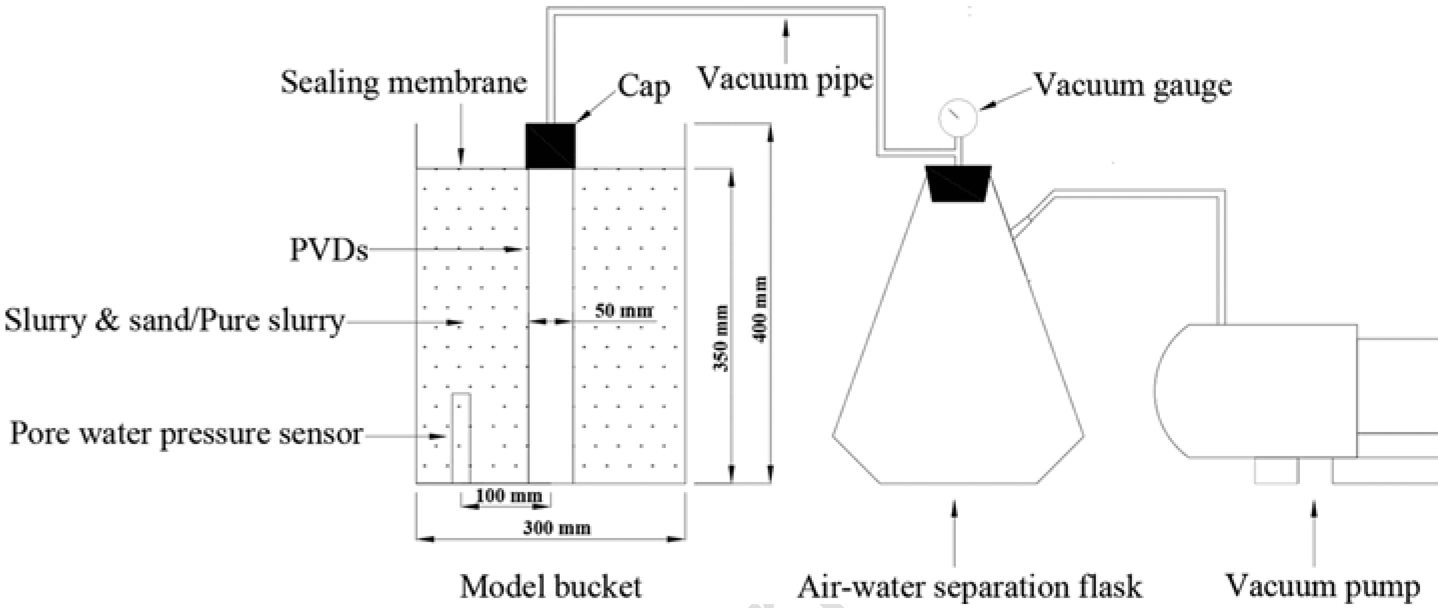

Figure 2. Comparison of pore water pressure versus time for samples containing various sand contents.

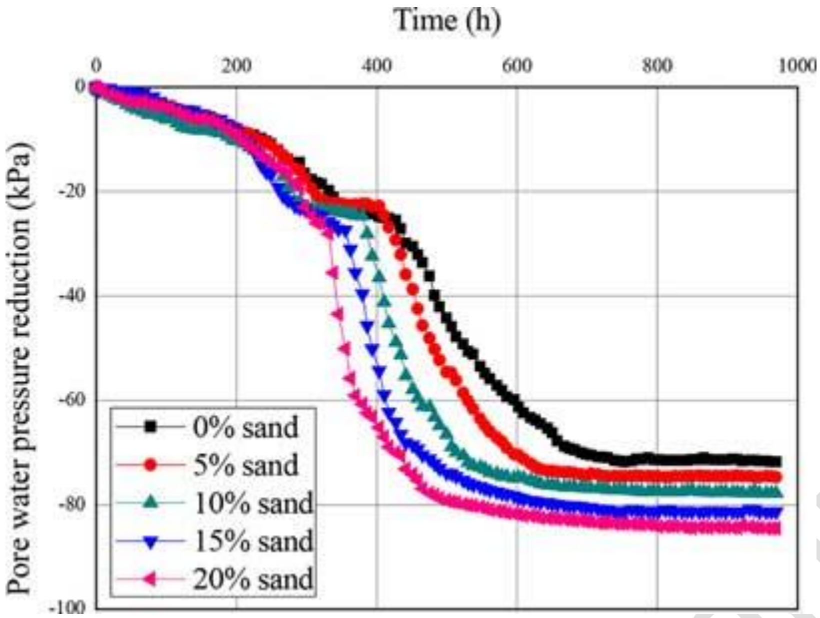

Figure 3. Comparison of pore water pressure versus time for samples containing various sand grain sizes.

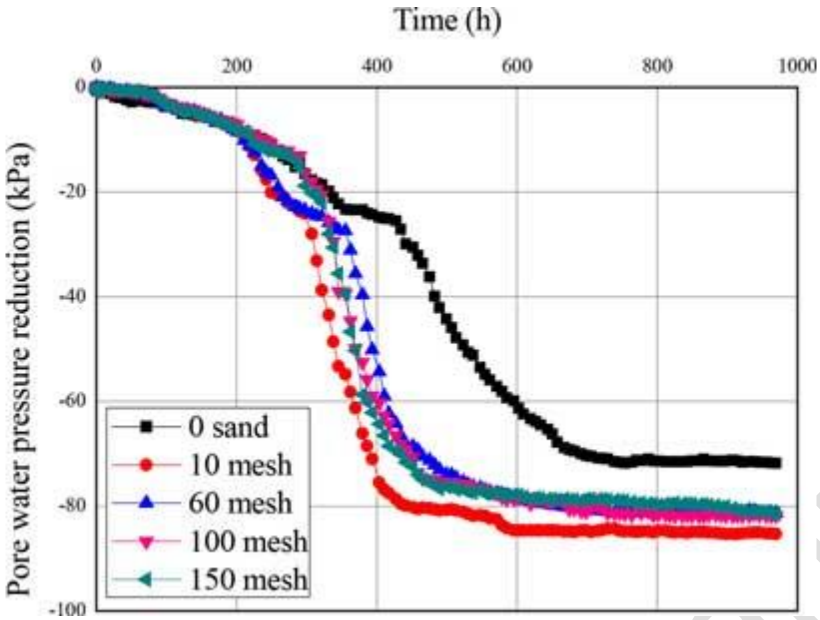

Figure 4. The changes in the discharged water volume with elapsed time for various sand contents.

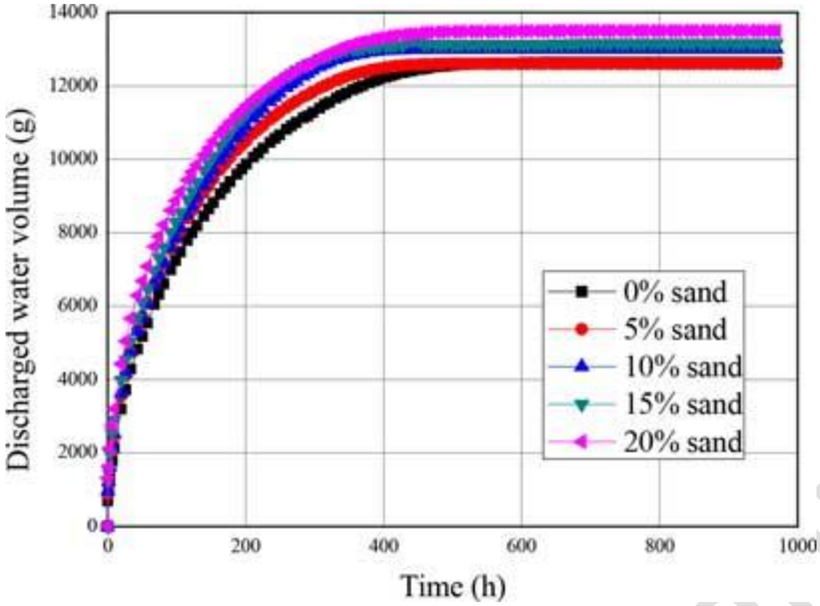

Figure 5. The changes in the discharged water volume with elapsed time for various grain sizes.

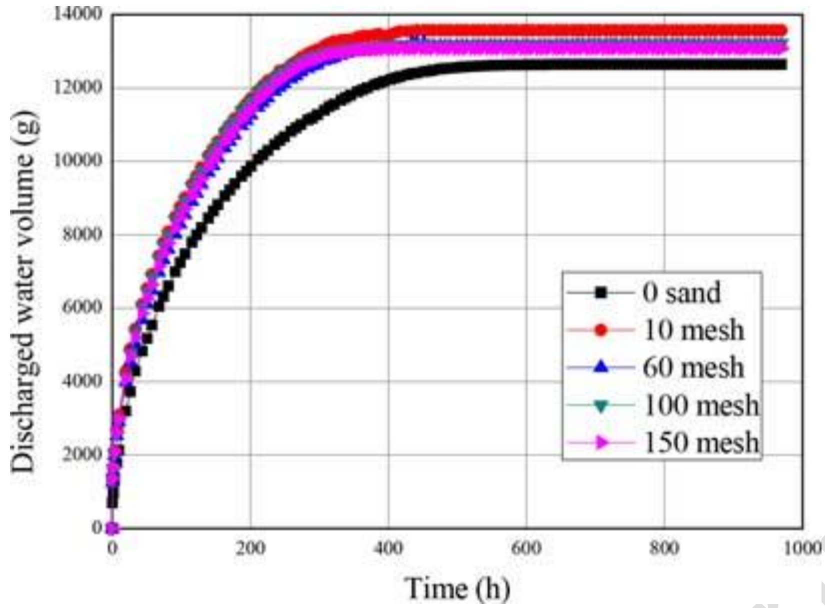

Figure 6. The relationship between the water content and sand content.

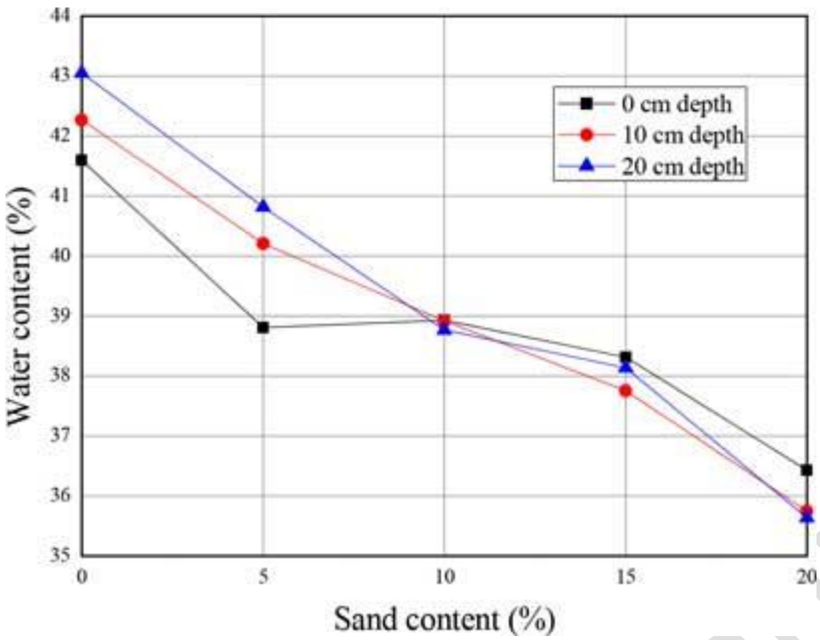

Figure 7. The relationship between the water content and sand grain size.

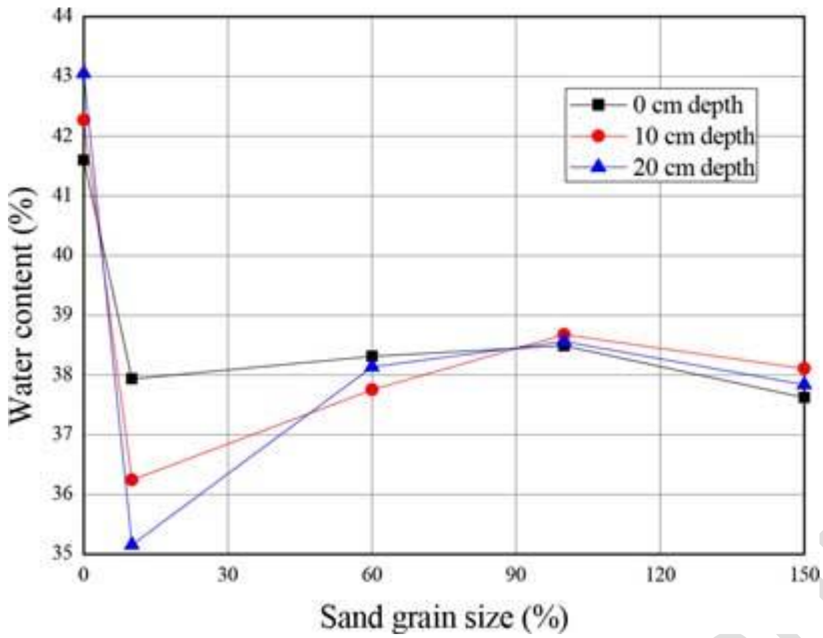

Figure 8. The variation of the vane shear strength with sand content.

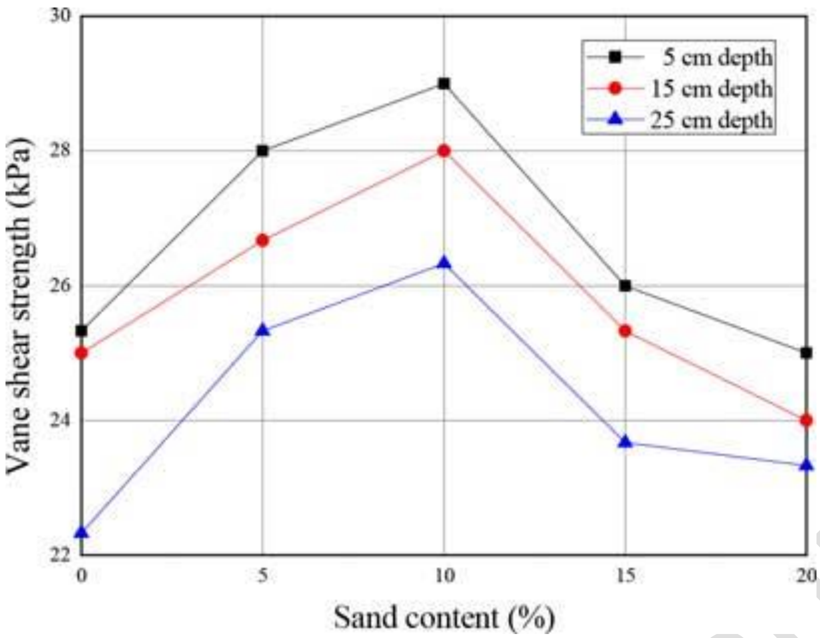

Figure 9. The variation of the vane shear strength with sand grain size.